

TECHNOLOGY NEEDS TO DISCOVER EARTH 2.0

Dr. Nick Siegler of the NASA Jet Propulsion Laboratory (JPL) began his talk by stating that the main goal of the Exoplanet Exploration Program technology effort is to enable future space missions to observe a planetary spectrum of a rocky planet in the habitable zone of its star and understand it in the context of potential life. He went on to say that the main exoplanet discovery tools, the radial velocity and transit techniques, which have discovered more than 95% of the more than 3,400 exoplanets, will not be the techniques to directly image exoplanets, which is needed to get a reflected light spectrum. Spectroscopy will be hard though because there simply aren't many photons available to use, but it will not be the biggest problem. The biggest problem will be suppressing the light from the stars which can be 10 billion times brighter than a rocky planet in the habitable zone of a Sun analog. Starlight suppression could be done in one of three ways: internal occulters (i.e., coronagraphs), external occulters (i.e., starshades), and nulling interferometers. The latter option is the least technologically mature of the options and one that NASA is not currently pursuing.

Coronagraphs

While the Hubble Space Telescope and the James Webb Space Telescope (JWST) both have coronagraphs, the Wide-Field Infrared Survey Telescope (WFIRST) will be the first space telescope with a coronagraph (or possibly a starshade) specifically designed for directly imaging exoplanets. WFIRST's Wide-Field Instrument (WFI) will arguably help answer questions regarding three of the biggest astrophysical areas: dark matter, dark energy, and exoplanets (via microlensing and coronagraphy). The telescope's coronagraph instrument (CGI) will be for the direct imaging and spectroscopy of exoplanets. WFIRST is in its formulation phase (Phase A) at this time. The project, telescope, and WFI are managed by the NASA Goddard Space Flight Center, while the CGI is managed by JPL. The project has now also been directed to study the compatibility of a starshade with WFIRST. The current state of the art for coronagraphs is the Gemini Planet Imager and the Very Large Telescope Spectro-Polarimetric High-contrast Exoplanet Research instrument. WFIRST would improve upon their contrast ratio capability by 2–3 orders of magnitude and also improve upon the ability to probe smaller planet-star separations (see Figure 3-3). Further technological advancement would be required to observe rocky planets in the habitable zone of stars at a distance of 10 pc and further.

Exoplanet Direct Imaging in the Optical and Near-infrared

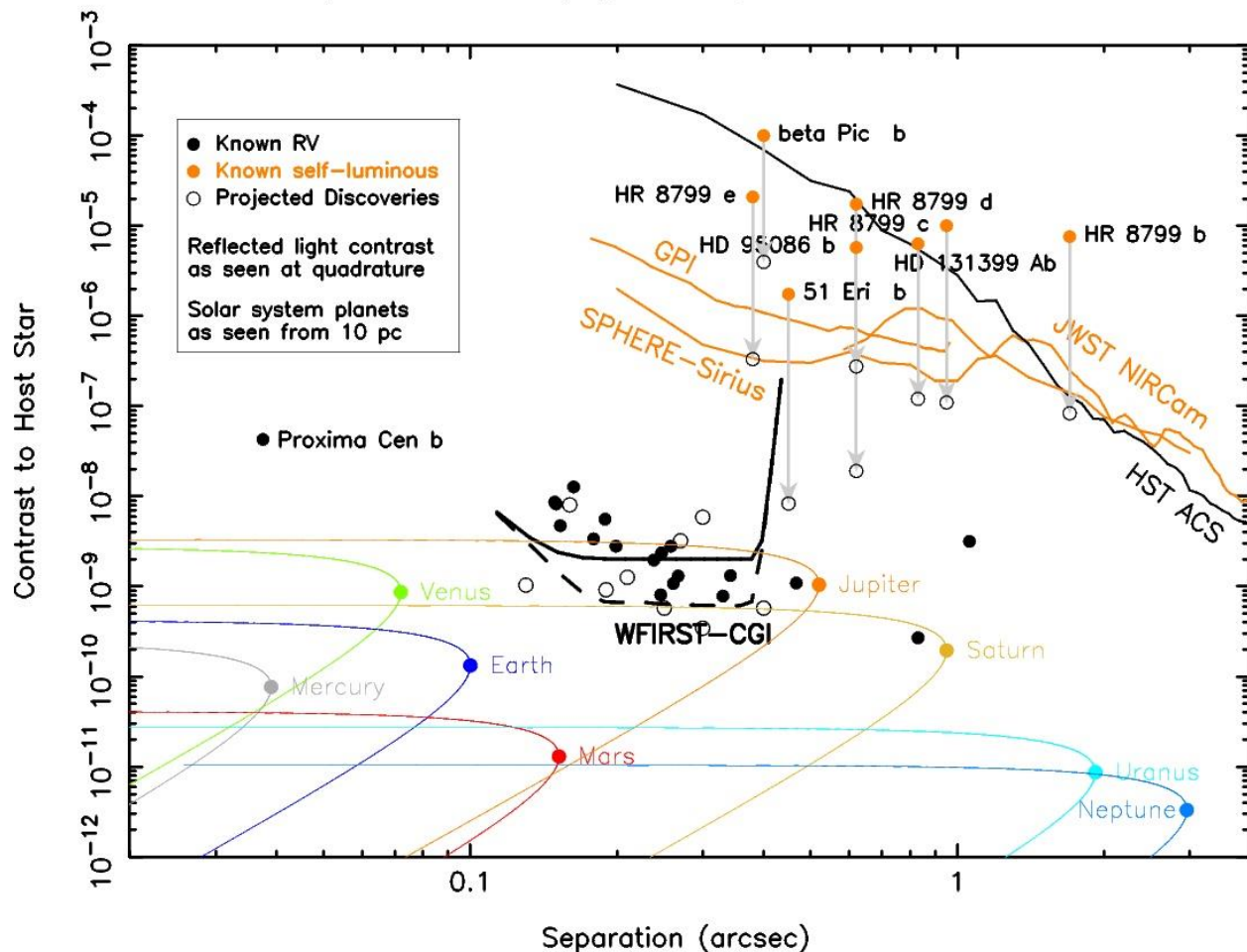


Figure 3-3: Direct imaging current and future planet-star contrast ratios (ratio of planet brightness to host star brightness) versus the apparent planet-star angular separation. The filled orange circles indicate the direct imaging of young, self-illuminous planets imaged in the near-infrared by ground-based telescopes (all are gas giants). Contrast ratios for the planets of the Solar System are for analogous planets placed 10 pc away and observed at visible wavelengths. The solid black circles are contrast ratio estimates of measured radial velocity planets, including Proxima Cen b. The orange curves show measured instrument performance at near-infrared wavelengths on ground-based coronagraphs. The Gemini Planet Imager (GPI) curve shows typical instrument performance while the Very Large Telescope's SPHERE instrument curve shows the best achieved instrument performance to-date on the star Sirius. Achieved performance with the HST/ACS coronagraph masks and the predicted instrument performance of the JWST/NIRCams masks are also shown. For consistency, the imaged planets discovered in the near-infrared are shown with vertical arrows pointing to the predicted contrast ratios at visible wavelengths (the WFIRST coronagraph is expected to conduct science between 442 and 980 nm). The current threshold requirement at 565 nm for the WFIRST coronagraph instrument (CGI) is shown as the thick solid curve; the black dashed line is the projected enhanced performance after further technology improvements before launch.

Siegler then showed a video from JPL about how a classical coronagraph works. As a star's light, depicted in the form of a wavefront, passes through the telescope it gets distorted by slight imperfections inherent in any telescope's optics. Diffraction adds concentric rings to the images. To see the planets, a mask is inserted to block most of the star's light and redirects the rest of the light to the outer edge. A washer-shaped object then blocks most of the redirected light. Because the planet's light comes in at an angle, it misses the first mask and goes through the center hole of the washer-shaped object. At this point, the planet's light is still obscured by the residual starlight leaking through. To reduce the amount of leaking starlight, a deformable mirror is used to correct the distortions in the incoming light beam. This

can then reveal the existence of a planet in the image up to a billion times fainter than the star. The video finished by saying that the planet's light can then be directed into a spectrograph for spectral analysis.

He then continued on to list what a future telescope with a coronagraph would need in order to study Earth-like planets in Earth-like orbits around Sun-like stars. It would need to improve its contrast ratio sensitivity from WFIRST's coronagraph by about two orders of magnitude. Deformable mirrors and image post-processing are fairly well advanced, but need to go farther. Integration times would be days to weeks typically, so the system needs to be incredibly stable. Otherwise, telescope vibrations and thermal distortions can cause blurriness. Siegler said that wavefront sensors need to be able to measure wavefront distortions up to 10 pm, a couple of orders of magnitude better than Hubble (the current best), and correct for them. The technology to phase large, segmented mirrors (which may be required to build telescopes with primary mirrors exceeding 4 m) to within at least nanometers is not yet developed. Because of the long integration times, photon rates will be measured in photons per minute, so detectors with ultra-low read noise are necessary, especially in the infrared. The size of the telescope is another question, especially with regard to a large, monolithic mirror versus a segmented mirror. He then showed an image of potential telescope architectures for 12 m segmented mirrors of various segment sizes and shapes (hexagonal to a more radial, pie-like structure). The main problem with segmented mirrors is that all the small gaps add additional layers of diffraction, and the primary purpose of a coronagraph is to remove diffraction.

Starshades

Siegler then showed an animation of a telescope with a starshade. They were two separate spacecraft with separate propulsion systems. When aligned, the starshade blocked the star's light revealing the reflected light of the planets. The starshade possesses a petal-like shape which serves to reorient the diffraction creating a dark shadow for the telescope. He claimed that, in many ways, a starshade is a simpler method than the coronagraph because the starshade is doing all the work. It drastically reduces wavefront-control requirements on sensitivity, segment phasing, and other corrections. It has a higher tolerance for error as long as the starshade performs as designed. The starshade would be tens of meters across and tens of thousands of kilometers away. The technological needs for a starshade are the ability to deploy and position its petals and maintain its physical stability, its ability to suppress the starlight, and its ability to fly in formation with a telescope separated tens of thousands of kilometers away. In the case of the latter, the telescope's lateral offset can only be a maximum of one meter. He then showed a demonstration of a starshade optical demonstration performed by Northrop Grumman in the Nevada desert which was able to detect a simulated planet one hundred million times fainter. Another experiment used a baseline of 2.4 km with a solar telescope to block out Arcturus and observe background stars. Another test best matching relative flight scaling, currently ongoing at Princeton University, has exceeded a contrast ratio of 10^{-8} .

The starshade will be challenging to manufacture. The petals, he said, will need to be about 6-8 meters in length and fabricated to a tolerance of about 100 microns. The petals will need to be deployed to millimeter-level precision. JPL tested a deployment method for the petals showing proof of concept. Another challenge is how to store an opaque starshade for launch and then deploy it without snagging or damaging itself since the starshade relies on its ability to remain opaque. A small, origami-like folding technique worked, so Siegler said that "JPL held back no expense" and performed a larger version (about half the size WFIRST would need) using corrugated cardboard and three interns. A recent prototype

demonstrated a smaller starshade, but with more flight-like materials such as Mylar and high-density polyurethane. He then added that they think they have figured out formation flying to meter-level precision using current equipment on WFIRST.

Siegler said that everything in his talk could be found in the Exoplanet Exploration Program Technology Plan Appendix from 2016 (the 2017 update is now released and can be found at their website). He then brought up a slide showing past and future NASA and European Space Agency exoplanet missions, such as CHEOPS and PLATO. He requested that future planning think favorably of exoplanets since we won't be able to analyze biosignatures and false positives or negatives unless we can directly image these exoplanets. Siegler finished by mentioning two NASA-chartered mission concept studies that will be considered for possible future missions that could dramatically advance the field of exoplanets: the Habitable Exoplanet Imaging Mission (HabEx), a 4-m monolithic mirror or 6.5-m segmented mirror, or the Large UltraViolet/Optical/Infrared Surveyor (LUVOIR), a 9–16-m segmented mirror.

Audience Participation

An audience member asked what the expected lifetime of a starshade would be and how many targets it could reach before running out of fuel. Siegler pointed out that this is a valid question due to the fact that micrometeoroids in space would likely pierce the starshade, limiting its lifetime. He said that, with multiple plies in the starshade, a micrometeoroid is unlikely to pierce perfectly orthogonal to the starshade where leaked light could do the most damage. He estimated a lifetime on the order of years. Pressed on the topic of fuel, Siegler explained a scenario which uses chemical propulsion to keep the starshade aligned with micro-thrusts and uses solar-electric propulsion for slewing to different targets. Another option is having two starshades so that one could be in operation while the other one was slewing.

Another participant pointed out that the tips of the petals have to be precise and sharp and then asked how they would clean dust off of them. Siegler said that they don't know yet, but agreed that the tips need to be razor thin, about one micron thick. Dust, typically on the order of a wavelength, could be a problem.

A biologist then asked why astronomers were so focused on Earth-like planets and so pessimistic about hot Jupiters. He thought that only about 30% of the NASA exoplanet program portfolio should be about Earth-like planets, not 100%. Siegler said that he embraced that view, but explained that by focusing the technology development on detecting Earth-like planets, you get the other planets for free. WFIRST, for example, would be able to detect hundreds of cold Jupiters, Saturns, and Neptunes too. Another audience member then commented that WFIRST will get about ten times more total planets than rocky planets in the habitable zone by doing an observational sweep in direct imaging.

That same commenter then raised a new question about whether the trick allowing a potential starshade to work with WFIRST would also allow one to work with the JWST. Siegler answered that NASA did study whether JWST could be designed to be starshade compatible but for technical and programmatic reasons ultimately decided against it. He then moved back to WFIRST and the collaboration between the JPL starshade and coronagraph teams and the Goddard spacecraft team. He said that the teams had found a relatively simple approach that addressed telescope-starshade alignment requiring minimal modifications to existing instrumentation. The WFIRST project has been asked to

continue carrying starshade compatibility in their designs subject to review. A final decision would likely be made by NASA no later than FY18.

An audience member then asked about the precision of the stability between the starshade and the telescope. Siegler noted that this is the flying formation issue. He said that the dark shadow of the starshade is about two meters in diameter and is cylindrically shaped. The lateral precision required needs to be within one meter, but the on-axis precision can have tolerances of hundreds of kilometers. The 1-m control precision has been done before on other spacecraft including those docking with the space shuttle, but the angular alignment required with WFIRST is on order of milli-arcseconds, which is in a whole new regime. The audience member then asked him how problematic he felt this was. Siegler then said that recent testbed demonstrations were relieving him of his concern. He no longer thought the two spacecraft sensing their relative positions is a problem and said that the necessary control has never been a problem.

A conference participant then asked what WFIRST could do for exomoons. Prompted by the audience, Siegler responded by saying that WFIRST's microlensing capabilities could potentially detect an exomoon, which would have a very unique lensing signature. However, spectral characterization would be impossible.